

CRYOGENIC UPPER STAGE SYSTEM SAFETY

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ABSTRACT

NASA's Exploration Initiative will require development of many new systems or systems of systems. One specific example is that safe, affordable, and reliable upper stage systems to place cargo and crew in stable low earth orbit are urgently required. In this paper, we examine the failure history of previous upper stages with liquid oxygen (LOX)/liquid hydrogen (LH₂) propulsion systems. Launch data from 1964 until midyear 2005 are analyzed and presented. This data analysis covers upper stage systems from the Ariane, Centaur, H-IIA, Saturn, and Atlas in addition to other vehicles. Upper stage propulsion system elements have the highest impact on reliability. This paper discusses failure occurrence in all aspects of the operational phases (i.e., initial burn, coast, restarts, and trends in failure rates over time). In an effort to understand the likelihood of future failures in flight, we present timelines of engine system failures relevant to initial flight histories. Some evidence suggests that propulsion system failures as a result of design problems occur shortly after initial development of the propulsion system; whereas failures because of manufacturing or assembly processing errors may occur during any phase of the system builds process. This paper also explores the detectability of historical failures. Observations from this review are used to ascertain the potential for increased upper stage reliability given investments in integrated system health management. Based on a clear understanding of the failure and success history of previous efforts by multiple space hardware development groups, the paper will investigate potential improvements that can be realized through application of system safety principles.

1. INTRODUCTION

America's Vision for Space Exploration, as defined by a Presidential announcement of January 14, 2004, calls for implementation of sustainable, affordable and reliable human programs to explore the Solar System and beyond. NASA is moving forward with development of new transportation systems to accomplish this vision. A new upper stage system is required to launch the Crew Exploration Vehicle (CEV)

and will be developed over the next few years by NASA MSFC.

The NASA Upper Stage System is a part of the crew launch system and will be designed to lift approximately 22 mT into Low Earth Orbit (LEO). As a result, it will be the largest upper stage system since the Apollo program. The upper stage, as shown in Fig. 1 will have a diameter of 5.5 meters. The NASA Upper Stage will be powered by a modified SSME that uses liquid hydrogen and liquid oxygen as propellants. As a result, the upper stage will include a main propulsion system that provides propellant feed to the engine and bleeds from the engine. Tank pressurization, inert purge, hydraulic, electronic and other subsystems will be required as well. Although this development will leverage the outstanding reliability record of the shuttle liquid propulsion system, the propulsion communities' best initiatives to develop a highly reliable upper stage are required.



Fig. 1. New NASA CEV Upper Stage

2. HISTORY OF UPPER STAGE SYSTEMS

2.1 Centaur

The U.S. has operated cryogenic upper stages since 1963. Centaur was the first cryogenic upper stage and evolved versions of Centaur continue in service after more than forty years of operating history. The evolution of the Centaur upper stage has progressed incrementally to the present version (Common Centaur)

flown on Atlas IIIA and Atlas V boosters. The evolution has been driven by national priorities, the commercialization of the Atlas/Centaur launcher after Challenger disaster, and the myriad of technology advances over four decades. All Centaur versions share construction techniques and materials for propellant tanks and major subsystems such as propulsion, tank pressure control and avionics. The different versions are distinguished by tank capacities, shape and booster vehicle integration. Centaur versions A, B and C were test and development versions that were flown between 1962 and 1965.

The single engine Centaur IIIA provided the foundation for development of the current version now being flown on Atlas IIIB and Atlas V series launch vehicles. The Centaur stage was lengthened by about 1.7 meters, increasing the propellant load from 16.9 to 20.8 tons. Other design changes include reliability enhancements associated with the RL-10-4-2 engine and stage structures, changes to reduce parts counts and to increase commonality between stage configurations. The Common Centaur stage is configurable as either single engine or dual engine using a single tank design.

2.2 Saturn-IV

The Saturn-IV was the first Saturn upper stage system developed. The Saturn-IV consisted of six Pratt & Whitney RL-10A-3 engines arranged in a hexagonal pattern delivering 41 tons (90,000 lb) thrust. A truncated cone-shaped thrust structure transferred engine force to the propellant tank walls. Just above the engines was an elliptical LOX tank which shared a common bulkhead with a cylindrical LH2 tank. Propellant tanks were of aluminum construction. Six separate LH2 feed lines wrapped around the LOX tank and fed each engine. A much more powerful upper stage was required when manned lunar landing became the U.S. national priority, and NASA resources were aligned to meet that goal. The six Saturn-IV upper stage flights between 1964 and 1965 were all successful.

2.3 Saturn-IVB

Saturn-IVB upper stage utilized a single J-2 Rocketdyne LOX/LH2 engine that provided 104 tons (230,000 lb) thrust. Propellant storage was cylindrical, constructed of aluminum, and consisted of an almost spherical LOX tank which shared a common bulkhead with the LH2 tank. Propellant mass was about 104 tons (230,000 lbs). The Saturn-IVB stage had restart capability. Twenty-two Saturn-IVB upper stages were launched between 1966 and 1975 and it proved to be a very reliable vehicle.

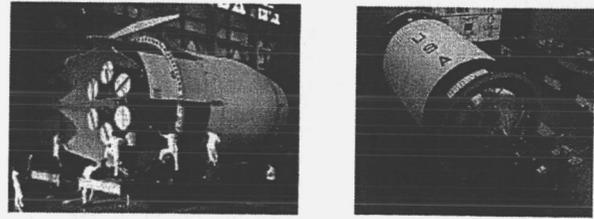


Fig. 2. Saturn-IV (L) and Saturn-IVB (R) Upper Stages

2.4 Ariane

The first successful Ariane 4 flights with the H10+/H10-3 upper stages occurred in 1992 and 1995, respectively. A new cryogenic upper stage was developed for the Ariane 5 launcher. Although derived from the H10 upper stages, the ESC-A upper stage required a redesign of propellant tanks to increase the available propellant mass needed to satisfy increasing payload sizes. In ESC-A, the LOX and LH2 tanks are separated and do not share common bulkheads. The LOX tank is a cylindrical aluminum vessel similar to H10. The LH2 tank is completely redesigned, adapting to the outer diameter of the Ariane 5. It is also of aluminum construction and uses the same bulkhead technology developed for the Ariane 5 booster LH2 tanks. The redesigned tanks allowed propellant mass to be increased to 14.4 tons. ESC-A is equipped with the same HM-7B gas generator engine used on previous Ariane upper stages. Engine burn time is extended to about 950 seconds with no restart capability.

2.5 Long March

After the U.S and the European Union, China became the third nation to successfully fly a cryogenic upper stage. The CZ-3 upper stage used a small, four combustion chamber YF-73 gas generator power cycle engine that provided 4.5 tons (9,900 lb) of thrust. The system had restart capability. This engine was very similar in appearance and performance to the HM-4 engine that was originally intended for the Ariane 1 launcher, but was never flown. The CZ-3 upper stage tanks carried 8.5 tons (18,700 lb) of propellant. This upper stage first flew in 1984; its 13th and final flight was in 2000.

The CZ-3A (B, C) upper stage was a significant upgrade from the original CZ-3 upper stage. Propellant capacity was increased by over 100% to 18.2 tons (40,100 lb), and the small YF-73 engine was replaced by a much more powerful dual thrust chamber YF-75 engine which was capable of providing 16 tons (35,300 lb) thrust with restart. This upper stage was also designed as the third stage for CZ-3B and CZ-3C launchers. The CZ-3A upper stage was initially launched in 1994.

2.6 H-II

The Japanese H-II upper stage was a significant scale up from the H-I. The common bulkhead propellant tanks were lengthened and widened, increasing propellant weight to 14 tons (30,900 lbs). A redesigned LE-5A hydrogen open expander cycle engine was used, boosting thrust to 12.4 tons (27,400 lbs). The H-II upper stage logged seven flights with one failure. It was first launched in 1994; the last flight occurred in 1999.

The H-IIA second stage was modified in several ways from its H-II precursor. It used a simplified structure consisting of separate propellant tanks held together by carbon composite support trusses rather than a common bulkhead design. The tanks were further enlarged, with propellant capacity of 16.6 tons (36,600 lb). The LH2 tank, is essentially the same structure supplied for Delta III/IV upper stages. The propulsion system is simplified, utilizing more reliable valves and an improved LE-5B engine which provides 14 tons (30,900 lb) thrust. The H-IIA upper stage inaugural flight occurred in 2001.

2.7 Delta Cryogenic Upper Stage (DCUS)

DCUS was developed in 1998. The propellant tanks carried a 16.8 ton (37,000 lb) propellant load. Propellant tanks were separate, self-supporting structures for simplified production and reduced technical risk. The LH2 tank was 4 meter (13.1 ft) in diameter. Propulsion was provided by a single Pratt & Whitney RL-10B-2 engine which produced 11.2 tons (24,700 lb) of thrust and was capable of restart in space.

The DCUS unit was modified for use on the Delta IV class launchers. Two Delta IV cryogenic upper stages are produced. Both use a 3 meter LOX tank suspended beneath the LH2 tank by an intertank truss. The propulsion system is unchanged from the Delta III upper stage. The Delta IV, 4-meter upper stage is identical to the Delta III version but with lengthened tanks for greater propellant load (~20% propellant load increase from 16.8 to 20.4 tons). A 5-meter diameter version with expanded tanks has been developed as upper stage for the heavier lift Delta IV launchers. Tanks were expanded another 33%, increasing the propellant capacity to 27.2 tons.

2.8 GSLV

The Geosynchronous Satellite Launch Vehicle (GSLV) marks the first use of hydrogen/oxygen propulsion in India. For the first two flights, ISRO purchased upper stages from Khrunichev in Russia, which ironically is now the only significant space power not to use hydrogen on its own rockets. The stage is designated

the 12KRB stage in Russia, and is powered by a KVD-1 engine.

3. CRYOGENIC UPPER STAGE FAILURE HISTORY

The Upper Stage for the NASA Crew Launch System (CLS) will be the largest upper stage developed since the Saturn program. All other upper stages have demonstrated payload to LEO of less than 10 metric tonnes whereas the new CEV upper stage will have a capability of approximately two and one-half times the other upper stages. As illustrated by Fig. 3, the thrust level of the propulsion system will be similar to that of the Saturn S-IVB stage. As a result, the upper stage will not use evolved subsystems of active flight vehicles. Instead, new systems based on legacy Space Shuttle main propulsion system will be utilized. Nevertheless, the root causes and solutions of historical failures such as manufacturing and inspection flaws have some importance for the new upper stage system development.

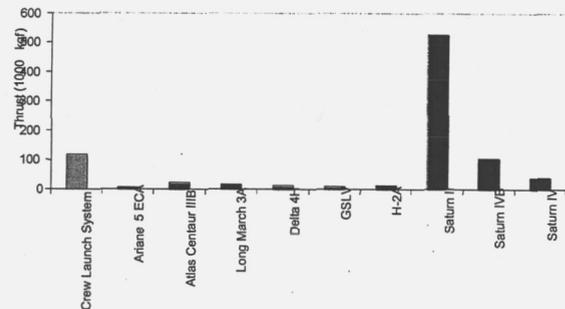


Fig. 3. Comparison of CLS to Other Launch Vehicle LOX/LH2 Upper Stages

Fig. 4 generally supports the conclusion that success rates of an upper stage system increase with experience, with more failures occurring early in the life of a system and increasing reliability as problems are resolved and technology improves. Early success rates for Centaur are much lower than other systems, but the Centaur program provided a learning curve for other systems that came into operation decades later.

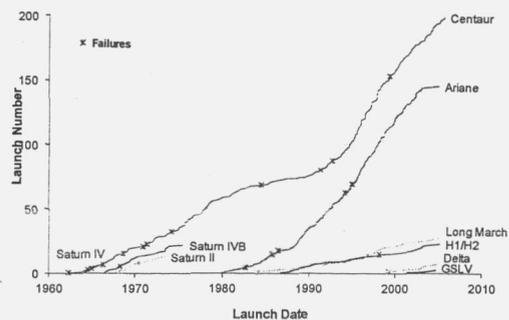


Fig. 4. LOX/LH2 Upper Stage Development Timeline

Overall upper stage reliability is improving, with average failure rates for the last decade of 3%. The Centaur upper stage is the reliability leader over the last decade with a failure rate of 1.2%. As might be expected, the upper stage systems with significantly more launches (Centaur and Ariane) have the lowest failure rates of all systems over the recent decade. These rates are based on 412 launch events many of which have multiple engines and many also had multiple upper stage burns. Therefore, there are significantly more upper stage system starts which require propellant management, engine spool-up, ignition and acceleration to full power. When considering sources of failure, the data shows 85% of failures are caused by propulsion system elements; engines or propellant supply systems, Fig. 5. Of the propulsion related failures, 40% are engine related. Although engines are commonly believed to be the largest failure source, the data indicate, in cryogenic upper stage systems, the engines have been about 33% of failures. As shown in Fig. 6, the cryogenic upper stage failure sources are widely distributed. A significant observation here must be that to maintain and improve cryogenic upper stage reliability, attention must be focused on all of the stage systems and subsystems.

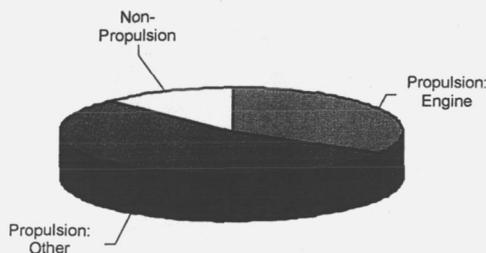


Fig. 5. Distribution of Cryogenic Upper Stage Failures

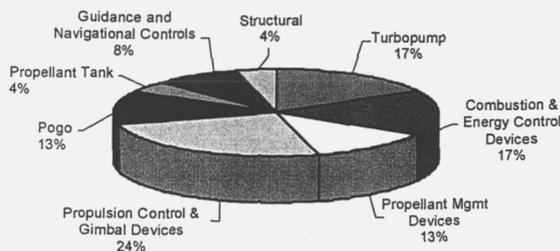


Fig. 6. Upper Stage Failure Sources are Widely Distributed

Early detection of potential failures allows in-flight remediation action such as engine throttle adjustments, engine shutdown or a decision to activate crew escape plans. Studies have shown that 70% of all liquid propulsion failures from 1964-1995 originated outside

the engine in systems such as propellant management, hydraulic, avionics, software or other subsystems. In this same time period, 41% of the failures are immediate and undetectable, whereas 37% are detectable with adequate time to initiate a response. The remainder of the failures may not be detectable or may not have adequate response time, if detected.

4. RELIABILITY IMPROVEMENT INITIATIVES

Several factors combine to create a failure-averse society with high expectations for safety of human spaceflight. As examples, commercial aviation operates with an outstanding safety record, automobiles are increasingly safer and many consumer items such as electronic equipment are extremely reliable. Although the Challenger and Columbia Space Shuttle accidents have sensitized all of us to the risks of spaceflight, in general, the American public and many decision-makers do not understand the degree of difficulty of spaceflight or the extent to which the industry is in its infancy.

As a result, effective risk management for the technical, cost and schedule aspects of the NASA Upper Stage system is required. This section outlines initiatives that will enable development of a highly reliable Upper Stage system including a robust, interactive system safety process and reliability analysis process working in conjunction with the design process, integrated system health monitoring and management systems, independent assessments, robust system engineering and integration design practices through concurrent engineering environments and validated models. Project leadership must relentlessly champion all of these initiatives with well-organized processes and due attention to the organizations safety culture.

4.1 Concurrent Engineering Environments

Information Technology advances have enabled innovators in geographically dispersed areas to collaborate as never before. Advances such as broadband connectivity, digital and mobile telecommunications as well as faster and more powerful PCs have enabled multidisciplinary analysis, design optimization at faster rates and more careful control of configuration. As a result, the resources and time required to design systems in a concurrent engineering environment (CEE) have been significantly reduced with improvements to the quality and reliability of the final product. The automotive industry was one of the leaders in outsourcing and serve as a model for aerospace innovation. Within the CEE, several design, development, testing and evaluation improvements or enhancements are needed. These include:

- Design for Six Sigma (DFSS)**
 DFSS is a widely recognized statistically based process that augments typical systems engineering functions. DFSS has been adopted by many key technology and aerospace industry companies including GE. Notable DFSS product development successes at GE include GE Power Systems commercialization of highly reliable gas turbines with breakthrough fuel efficiency performance, and GE Medical Systems introduction of a new generation of soft tissue scanning systems. The DFSS methodology has been successfully used in the development of advanced industrial gas turbine sealing systems. Specialized probabilistic tools such as Technology Identification, Evaluation, and Selection (TIES) have been used within the framework of DFSS to provide stochastic evaluation and down-selection of multiple technology combinations for advanced high-bypass jet engines and for space transportation systems.

- Probabilistic Design and Analysis**
 Probabilistic design and analytical techniques can add value to the design process, as well. As illustrated by Fig. 7 the upper stage preliminary design will be evaluated using fault tree and failure mode and effects analysis to discern component criticality. Non-critical components will be designed with traditional deterministic techniques whereas critical components will be assessed with a probabilistic design approach. Probabilistic design approach is most applicable for components that exhibit: variation in material properties, critical dimensional tolerances, modeling deficiencies, and environmental uncertainties.

- Internal and Independent Technical Reviews (ITR)**
 Thorough internal design reviews are needed to identify design deficiencies and risks to program success. Multiple spacecraft failure board results have cited a lack of penetrating reviews as a source of error that ultimately contributed to loss of spacecraft. Focused ITR's should evaluate both flight and ground systems maturity including application and management of redundancy, performance margins, and use of heritage hardware and validation of its applicability. Ultimately, the ITR should assure that the design is maturing toward a stable design that meets the design requirements with margin. The ITR should operate with minimal intrusion into mainstream design project work. For both internal and independent design and technical reviews, the project must have allocated schedule contingency to allow for incorporation of review findings and recovery. Without this purposeful recovery phase, project resistance to identified improvements will naturally occur.

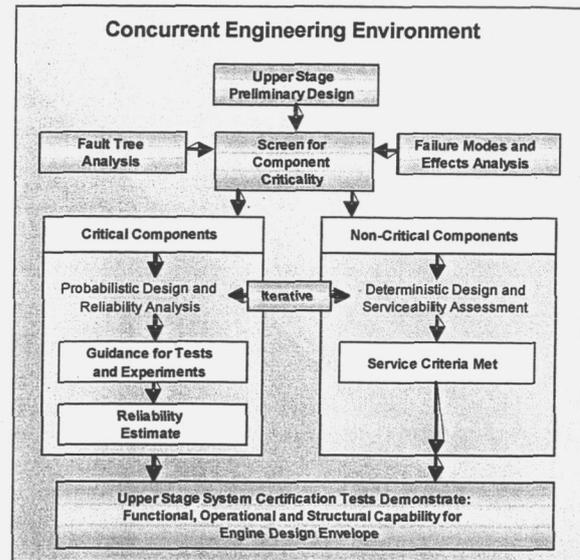


Fig. 7. Candidate Upper Stage Certification Approach

4.2 Reliability Analysis

The ARES Cost-Effective Reliability Analysis (CERA) determines the distribution of an Upper Stages actual reliability throughout the course of the design effort allowing adjustments by the project design team. The process includes uncertainty in a reliability analysis that is associated with the component's normal variability or lack of knowledge. Best engineering judgment, surrogate data, test data, or actual component data is used with standard Bayesian processes to determine the best representation of a component's failure probability or failure rate. The reliability analysis determines the major reliability drivers based on either the uncertainties associated with the component's failure rate, or how the components operate within the designed system. By addressing and managing the major reliability drivers one can identify the most cost-effective way to improve the system's reliability.

4.3 Damage Tolerance Testing

Although the cost of the time required to demonstrate high reliability through testing alone is prohibitive, testing has a significant role in reliability improvement. As an example, damage tolerance testing from the DOD Engine Structural Integrity Program (ENSIP) program has been successfully used to validate models used in the probabilistic design of critical components. Damage tolerance testing may include evaluation of pre-flawed components to evaluate crack growth and design sensitivity to crack size. Fig. 8 compares commercial and military engine rotor failures and demonstrates the application of damage tolerant design principles and testing has reduced the number of distress events occurring in military engine rotors. The large reduction noted in military engines' rotors failures starting in 1979

is credited to the ENSIP program. Similarly, the large reduction in this same metric in commercial engines in 1986 is apparently a result of the ENSIP approaches being applied to commercial engines approximately eight years later, a typical military to commercial technology transition time.

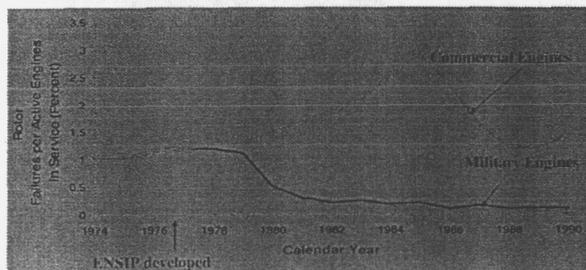


Fig. 8. Air Force Engine Development

The DoD's ENSIP process is quite complex and is the result of extensive development. Although this approach should yield major reliability improvements for the upper stage system development, adequate preparation for the NASA-contractor team is required before ENSIP type requirements are imposed on a new development program. The failure modes for space systems are not the same as aircraft systems and the environments are very different. A pilot advanced development project to explore and develop similar concepts for space systems would provide the readiness to use a Space ENSIP for future Exploration systems.

4.4 Integrated System Health Monitoring and Management

Integrated System Health Monitoring and Management (ISHM) is an emerging competency for all highly reliable flight systems. Experiences from all U.S. manned space programs accidents demonstrate that complete, accurate assessment of vehicle conditions is required to assure crew safety and mission success. While potential benefits of this system are easily recognized, further development efforts are required. NASA is currently funding technology development efforts led by Penn State University and NASA SSC. Incremental development of the ISHM provides an opportunity to mature the system before application to active flight systems. Key areas for future development include: selection of ISHM architecture(s), smart sensors, health detection algorithms, and communication protocols. Methods for validation of these systems prior to activation in a flight system are also needed.

Propulsion ground test facilities offer an excellent and realistic venue for large-scale health monitoring technology demonstrations and afford the opportunity

for inducing failures that must be detected and acted on to maintain safe conditions. Health management should incorporate fault diagnostics that are capable of detecting, isolating and identifying faults in subsystems or components. Information produced by the fault diagnostics process in the control of the ground test systems may then be utilized to develop integrated fault-adaptive control approaches for flight vehicles. The Space Shuttle and other flight vehicles offer potential as technology demonstrators as well.

4.5 Organizational Attributes for Design of Highly Reliable Launch Systems

One of the primary drivers for highly reliable designs is the structure and safety culture of the design organization. Studies have shown that well-defined organizational processes allow effective communication between contributing design team members. As an example, the decision-making process is well documented and well understood by all design team members. This process includes ample time for discussion and debate of competing concepts and a positive view of system safety. Roles and responsibilities of all team members are defined and understood by others.

Design organizations that have a strong, interactive system safety culture tend to produce highly reliable designs. Based on studies after the Chernobyl nuclear accident and Challenger tragedy in 1986, safety culture is the enduring value and priority placed on safety by every design team member. It refers to the extent to which individuals and groups commit to personal responsibility for risk reduction and will act to preserve, enhance and communicate system safety. Safety culture is reflected in an organizations willingness to develop and learn from errors or near misses. Further, this safety culture recognizes and encourages contributions from all team members, but is championed by project leadership. It is relatively enduring, stable and resistant to change.

Indicators that help measure the strength of these attributes include organizational commitment, leadership and management involvement, employee empowerment, a strong rewards system and reporting systems.

5. SUMMARY AND CONCLUSIONS

This paper traces the historical development of cryogenic upper stage systems and compares previous efforts with the new NASA Upper Stage. It outlines important initiatives to assure the reliability of the new NASA Upper Stage including integrated system health monitoring and management, damage tolerance testing, technical reviews, probabilistic design and analysis, a

robust reliability analytical process that is closely-coupled to the design process, and a sound design organizational structure that embraces system safety as an integral aspect of the design process.

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